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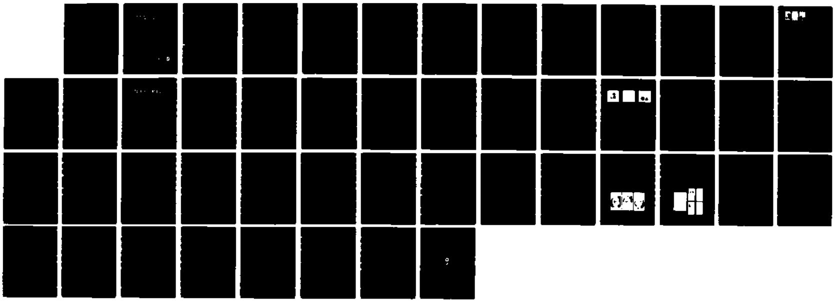

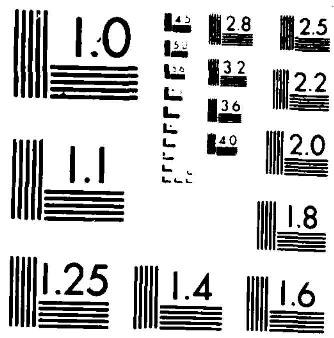

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REAL-TIME IMPLEMENTATION OF NONLINEAR OPTICAL PROCESSING FUNCTIONS

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Optical data processing has not yet achieved its potential of increased capacity and speed compared with conventional electronic techniques, primarily for lack of a practical real-time image modulator, and because optical techniques have been almost exclusively limited to linear operations. The continuing research outlined in this report attacks these issues by studying the implementation of real-time nonlinear parallel-processing techniques. The various implementations studied in this program for the most part employed real-time liquid-crystal light valves developed and specially modified for these tasks by Hughes Research Laboratories. One approach we investigated early in the program was to modify and characterize the twisted-nematic liquid-crystal (LC) devices, and then use them in a coherent optical data-processing apparatus using special half-tone screen masks, custom designed for special functions at USC in a cooperative effort under an AFOSR grant. Using the half-tone mask technique, we demonstrated logarithmic nonlinear transformation, permitting us to simplify multiplicative images and perform homomorphic

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filtering. Furthermore, a novel analog-to-digital converter based on a modified pure birefringence LCLV was developed. It can perform real-time parallel processing using incoherent light, and it promises high data throughput rates. In addition, a novel device that converts light intensity variations to LC grating period variations was fabricated, and is currently being evaluated and improved. This device permits nonlinear functions to be implemented directly without the need for specially made half-tone masks. Besides nonlinear analog functions, this variable grating mode (VGM) device has demonstrated the capability of performing digital logic. Logical functions are merely special cases of nonlinearities. A novel technique for spoiling the long-range order of the grating domains has made a remarkable improvement in VGM response time from seconds to tens of milliseconds. A theoretical and experimental study of the behavior of the liquid crystal molecules in the VGM effect has yielded much information concerning molecular orientation and thresholds. A study of the dynamics of grating formation and relaxation was carried out in order to improve the VGM response time. In cooperation with USC, the final studies of the physical basis of the variable grating mode (VGM) effect were brought to a close this year.

We completed research on a novel optical method for dividing two images or arrays of data in real-time. There are no other reported methods of optical division! Related to this, two further inventions were conceived, optical matrix multiplier and an all optical matrix inverter. The matrix inverter is the first invention of a fully optical system to perform this important function with many system applications. Separately work has been initiated in cooperation with Dr. A. Tanguay at USC on the general limits and optimizations of optical systems. Another task pursued was the conception and experimental demonstration of a new technique for subtracting images in real-time using a single LCLV. This simplication of earlier subtraction schemes should prove useful in a variety of fields including surveillance, robotics and inspection and control of manufacturing processes.

During this program period we continued in a new and very important direction begun at the end of the last period. We are developing an all optical associative memory using holographic storage of the data base and phase conjugate mirrors to provide feedback, nonlinear thresholding and gain. Associative memories can, for example, recall the closest memory to a given partial, noisy or corrupted input addressed to the system. They can, among other things, classify inputs and also heteroassociate one image with another. We have demonstrated grey-level image recall and image recall with multiple stored images from partial-image input to the system. We have studied the analogy between our system and other neural network models of associative memory. We have also studied the theoretical limits of storage capacity and signal to noise ratio of our model. Alternative concepts and devices that exhibit, like VGM, the fundamentally new and important property of converting intensity variations into positional variations, but which potentially are faster yet, were further investigated in this period.

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SECTION 1

INTRODUCTION

For the past two decades optical data processing (ODP) has promised a vast increase in processing capacity and speed over conventional electronic techniques. This promise has never been fulfilled for several reasons, most notably because of the lack of a practical real-time image modulator, or light valve, and because optical techniques were almost exclusively limited to linear operations. These restrictions have been removed by the development of the liquid-crystal light valve (LCLV) by Hughes Research Laboratories (HRL), and by nonlinear parallel-processing techniques developed by the University of Southern California (USC). Thus, it is important to determine how successfully nonlinear parallel-processing techniques can be implemented in real time with the various LCLVs. In addition, other new optical technologies, highly developed at HRL, such as four-wave mixing and phase conjugation have inspired a novel research direction for this program in the field of optical associative memories and neural networks as models for computing. Here the phase conjugation provides the desired nonlinearities.

The implementation and evaluation of these techniques have a direct relationship to current Air Force technology. Pertinent Air Force interests include multidimensional real-time signal and image processing with varied applications, including nonlinear filtering for trajectory control and guidance, "smart" sensing, picture processing, and bandwidth compression, image and target recognition and symbolic processing. These technologies could benefit substantially from the increased processing capacity and speed that this research may yield.

In this section we describe our optical methods and the motivation for studying a real-time application of those techniques. In Section 2 we describe the progress made during the current program year.

Until now, specified nonlinear operations have been performed only with great difficulty. Coherent optical techniques are essentially restricted to linear operations. Digital processing to produce nonlinear transformations is possible, but only in a slow, serial fashion. Certain nonlinearities can be produced by special photographic techniques, but the speed, accuracy, reproducibility, and dynamic range of these techniques are limited.

We have been pursuing different tasks to attempt to overcome these shortcomings. The first made use of special half-tone screens to modulate the input image in conjunction with coherent optical processing. This technique had made it possible to implement nonlinear effects when higher orders of the half-tone diffraction pattern are examined by spatial filtering. Sawchuk and Dashiell of USC have shown, using specially fabricated half-tone screens, how a very wide class of two-dimensional point nonlinear functions can be implemented with a large dynamic range as a function of screen design and diffraction order. The nonlinearities can be continuous or discontinuous. Operations such as taking logarithms, exponentiation, level slicing, intensity bandstopping, and histogram equalization can be performed. We have expanded the half-tone screen technique by substituting a real-time photo-modulated LCLV for the static photographic recording medium, and we have successfully demonstrated a logarithmic nonlinear transformation using this technique. This transformation is useful for homomorphic-filtering applications as we have demonstrated. In cooperation with USC, we have also studied the performance potentials and limitations of this implementation and how to iteratively modify and improve the LCLV and half-tone masks.

A second general method which we have studied also overcomes the limitations of serial or photographic processing; it employs, in one realization, a liquid-crystal effect variable grating mode

(VGM) that can, when incorporated into a new type of photoconductive structure, automatically map image intensity variations into positions in Fourier space. Filtering and reconstructing can then yield many desired nonlinear transformations of the image without the need for specially constructed half-tone masks. A new additional parameter, the intensity, has thus been made available for optical image and data processing. Recognizing that logical operations are merely a special case of nonlinear operations, we have demonstrated a unique and highly advantageous optical computing scheme using the VGM technique. The VGM device is still in an early stage of development and much material research and device development would still be needed to make it into a practical, real-time, reliable optical image modulator. We have discovered and investigated a novel technique for spoiling the long-range order in the VGM domains by modifying the substrates in order to effect a remarkable improvement in the temporal response of the device from the previous values of many seconds to the present value of tens of milliseconds. Empirical and theoretical studies of the basic VGM effect have been made, including the study of the detailed optical polarization properties of the VGM optical diffraction patterns and the minimization of free energy calculations, with the goal of completing the modeling of the molecular configuration of the liquid crystal system. The results of these studies may result in the molecular engineering of liquid crystal mixtures with more rapid temporal response. The studies of the physical nature of the VGM effect are essentially done and were completed in this program period in collaboration with USC. We are also studying alternative practical realizations of intensity to positional mapping which may overcome some of the shortcomings of VGM, yet retain the great flexibility offered by intensity-to-positional coding.

We also had devised in the last period a method using LCLVs to enable, for the first time, the entirely optical analog division of two arrays of numbers or images, pixel by pixel in real-time. This work was brought to conclusion with a successful experimental demonstration. In addition a technique to perform real time substraction using a single spatial light modulator was also developed.

We began in the last period an important new direction for the program, the all optical associative memory. This work was emphasized in the current reporting period.

SECTION 2

PROGRESS DURING CURRENT PROGRAM PERIOD

During this program period we pursued several new tasks. Work was initiated in cooperation with Dr. A. Tanguay at USC on the general limits and optimizations of optical systems. Also in cooperation with USC, the final studies of the physical basis of the variable grating mode (VGM) effect are being brought to a close. Alternative spatial frequency to positional mapping schemes, based on gradient index beam deflection, were also investigated in this period. A new and very important direction for the program was taken with the inception of work on an all optical associative memory using holographic storage of the data base and phase conjugate mirrors to provide feedback nonlinear thresholding and gain. Associative memories can, for example, recall the closest memory to a given partial, noisy or corrupted input addressed to the system. They can, among other things, classify inputs and also heteroassociate one image with another.

A. OPTICAL ASSOCIATIVE MEMORY

In this program period we have developed a new task: the research and development of an all optical associative memory. Partial noisy or incomplete information addressing the associative memory system will retrieve the closest stored complete image. Our novel approach is in part to store multiple 3-D images or data bases globally in the holograms. Each of the multiplexed images is stored with its own angularly coded reference beam in the recording phase. In retrieving the information, retroreflection, nonlinear thresholding, feedback, and gain are achieved with phase conjugate mirrors. A technical discussion of our concept and the results of our preliminary experiments are described in the following reprint of a recent Optics Letters paper.

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Associative holographic memory with feedback using phase-conjugate mirrors

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We describe an all-optical associative memory system that uses a holographic data base. Phase-conjugate mirrors are used to provide optical feedback, thresholding, and gain. Analysis and preliminary experiments are discussed.

The principle of information retrieval by association has been suggested as a basis for parallel computing and as the process by which human memory functions.[1] Various associative processors have been proposed that use electronic or optical means. Optical schemes,[2-7] in particular those based on holographic principles,[3,6,7] are well suited to associative processing because of their high parallelism and information throughput. Previous workers[8] demonstrated that holographically stored images can be recalled by using relatively complicated reference images but did not utilize nonlinear feedback to reduce the large cross talk that results when multiple objects are stored and a partial or distorted input is used for retrieval. These earlier approaches were limited in their ability to reconstruct the output object faithfully from a partial input.

Recently a matrix-based associative memory model using feedback and nonlinear thresholding was described.[1,9] The concept has been demonstrated for one-dimensional data by digital computation as well as by optical means.[4] Storage of two-dimensional data (images) would result in a four-dimensional association matrix, making the problem much more difficult to handle electronically or optically.

It is the purpose of this Letter to present a parallel optical associative memory system with feedback that is implemented with holograms and nonlinear optical elements. The global memory, a hologram, is capable of storing multiple three-dimensional objects, thus overcoming one of the limitations of the matrix-based approach. The nonlinear interaction is achieved by using phase-conjugate mirrors (PCM's) to provide the regenerative feedback, thresholding, and amplification mechanism.

The formation of a hologram involves the exposure of a light-sensitive medium with two coherent wave amplitudes $A(u, v)$ and $B(u, v)$ generated by two objects a and b. When the hologram is irradiated by a complex wave front $\hat{A}(u, v)$, which is a distorted or incomplete version of $A(u, v)$, the amplitude transmitted by the developed hologram is proportional to

$$\hat{A}|A + B|^2 = \hat{A}(|A|^2 + |B|^2) + \hat{A}A\bar{B} + \hat{A}\bar{A}B, \quad (1)$$

where a bar (e.g., $\bar{A}$) indicates the complex conjugate of the unbarred function.

The last term of this expression is essentially the convolution of the object b with the correlation of $\hat{a}$ and $\bar{a}$. For most natural objects there is sufficient phase variation so that if $\hat{a}$ is identical, or close, to a, their correlation provides a sharp peak and b is faithfully reconstructed.

Multiple objects b_i can be stored in a hologram, each associated with a different reference wave a_i. This by itself acts as a linear associative memory, so that a distorted $\hat{a}_i$ can be represented as a weighted superposition of several a_i, without discrimination.[2,3] To display the image b_i most closely associated with $\hat{a}_i$, one needs to eliminate all other images, retaining only $\hat{A}_i\bar{A}_iB_i$.

A common use of associative memories is one in which, given $\hat{a}_i$, one is interested in the determination of a_i, the stored undistorted record, rather than in its mate b_i. The mate, however, is necessary to help identify the record i; thus, if the last term in Eq. (1) is used to readdress the hologram, one obtains

$$\begin{aligned}\hat{A}\bar{A}B|A + B|^2 &= \hat{A}\bar{A}B(|A|^2 + |B|^2) + \hat{A}\bar{A}BA\bar{B} + \hat{A}\bar{A}B\bar{A}B \\ &= \hat{A}\bar{A}B(|A|^2 + |B|^2) + \underline{(\hat{A}\bar{A})|B|^2A} + \hat{A}\bar{A}^2B^2. \end{aligned} \quad (2)$$

Note that for most objects a and b, their phase variations will result in uniform intensity distributions $|A|^2$ and $|B|^2$ at the hologram. These terms will only slightly alter the transmitted amplitude, leaving its phase almost unaffected. (If $\hat{A} \equiv A$ the phase is perfectly regenerated.) As a result the underlined term represents a close restoration of the field distribution A, which in turn reconstructs object a. It should be noted that this discussion treats a single image recorded on a hologram, analyzed in a linear-approximation model. If multiple images were present, the analysis would show that there is poor discrimination between the desired image and the cross terms. The addition of nonlinear elements that provide thresholding and feedback improves the discrimination, as described below.

Psaltis and Farhat[4] in a recent paper briefly described an associative memory scheme based on a two-hologram configuration. The thresholding element is in the image portion of the loop, similar to Hopfield's[9] approach.

In our system we combine the principles of holographic memories and PCM's to implement a novel nonlinear holographic associative memory. Only a single hologram is needed in this configuration, and it is simultaneously addressed by the object as well as by the conjugate reference beams, the latter acting as the key that unlocks the associated information. PCM's are used for beam retroreflection as well as for gain and thresholding. This provides the necessary nonlinearity, emphasizing only the strongly correlated signals.

The memory consists of a hologram in which a stored object, a_i, is written using a plane-wave reference b_i, as illustrated in Fig. 1. The two legs of the memory consist of a reference leg and an object leg, each with its respective PCM. A partial or distorted input object $\hat{a}_i$ generates a distorted reference beam $\hat{b}_i$. The distorted reference $\hat{b}_i$ is focused by the lens onto PCM 1. PCM 1 is a thresholding conjugator, e.g., a stimulated Brillouin scattering cell or a self-pumped photorefractor. The desired plane-wave reference component of $\hat{b}_i$ forms a bright spot on PCM 1 (PCM 1 is in the Fourier plane of the lens). PCM 1 will select this bright region (thresholding), conjugate it, and reflect it back toward the hologram as a partially restored reference $\bar{b}_i$. This partially restored reference then illuminates the hologram and generates a partially restored object $\bar{a}_i$, which is conjugated and reflected by PCM 2 back to the hologram (without thresholding). The round trip is then completed and the cycle repeats. The image restoration proceeds at a rate governed by the phase-conjugate resonator's response time.

If the combination of PCM 1 and PCM 2 has gain comparable with the losses in the system, the output will converge to a real image of the complete stored object. If a fixed hologram is used, many objects can be stored in the hologram by using different reference waves. The memory will then select the stored object that has the largest correlation with the input object.

The object and reference legs are self-aligning with respect to the hologram because of their phase-conjugate nature. There is an alignment requirement, however, between the input $\hat{a}_i$ and the stored object a_i. The translational alignment accuracy required can be reduced by utilizing a Fraunhofer (Fourier-transform) hologram. The Fourier transform of most objects has a large zero-order term, placing a large dynamic range requirement on the hologram to avoid distortions of the stored object. However, such distortions may be desirable since the relative reduction of the zero-order term will result in the enhancement of high-frequency components, i.e., edges, which will help to orthogonalize the stored objects and improve discrimination. The use of $BaTiO_3$ as a PCM also has been shown to provide edge enhancement.[10]

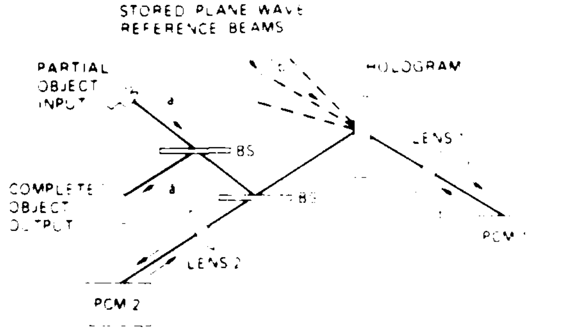

Fig. 1. Implementation of an associative holographic memory using PCM's.

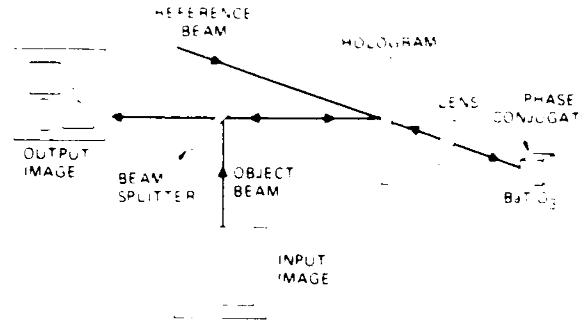

Fig. 2. Schematic of experiment that demonstrated the complete object image reconstruction from a partial input image.

A possible variation of the system would be to use a spatially modulated reference beam in the formation of the hologram. For example, the stored object a_i could serve as its own reference beam if a beam splitter were employed in the proper location. Furthermore, a different object could serve as a reference, resulting in a heteroassociative memory.

We have demonstrated in preliminary experiments the total reconstruction of an image when only a partial image addressed the system. This was done in the single-pass configuration shown in Fig. 2, which consisted of a single-image hologram, acting as the memory element, and a nonthresholding PCM. The hologram was recorded at 514.5 nm using a Newport Corporation thermoplastic holographic camera. The PCM was produced by degenerate four-wave mixing in the photorefractive crystal $BaTiO_3$. Typical parameters for PCM operation are wavelength 514.5 nm; forward and backward pump fluxes 3.3 and 11.5 W/cm^2, respectively; internal pump–probe angle 26°; and internal angle of grating k vector to c axis 13°. The hologram was generated by recording the interference of an object beam [a transparency of four geometrical shapes (Fig. 3A)] and a spherical diverging reference beam at the hologram plane. On illumination of the hologram, or of part of it, by the object beam, the diffracted beam propagating in the original direction of the reference beam becomes the probe beam for a degenerate four-wave mixing (DFWM) system. The signal generated by DFWM is the phase conjugate of the probe, i.e., the reference beam propagating in reverse. When the DFWM signal illuminates the hologram a portion of it is diffracted, recreating the object beam. This recreated object beam has all the infor-

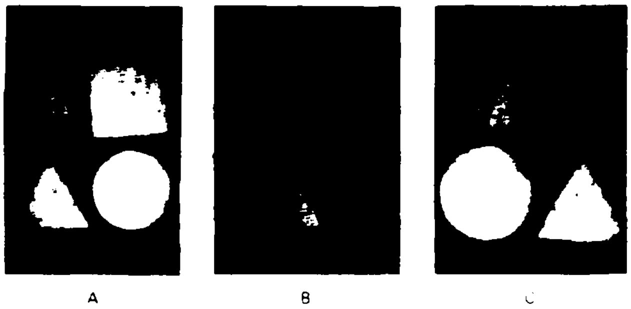

Fig. 3. Experimental results: A, image stored in memory; B, incomplete input image; C, associated output image (reflected by a mirror).

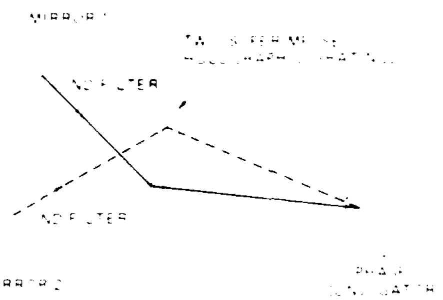

Fig. 4. Schematic of experiment that demonstrated operation of a phase-conjugate resonator with multiple intracavity holographic gratings.

mation originally contained in the input image. Thus, by using the input of a partial object image (Fig. 3B), merely one of the four geometrical shapes, the entire object image of four shapes was regenerated (Fig. 3C). As expected, the system did not reconstruct the object image when the input object was translated from the original position at which the hologram was recorded. This verifies that the complete output object was indeed generated by the incomplete input object and not by any other beam.

In order to simulate thresholding and address the issue of angular multiplexing of objects, we demonstrated that a phase-conjugate resonator can operate with multiple intracavity holographic gratings (keeping in mind that a hologram can be decomposed into a set of simple gratings). The gratings were made in dichromated gelatin and had a $\simeq 60\%$ diffraction efficiency at 514.5 nm. The resonator, shown in Fig. 4, consisted of the phase conjugator (a pumped crystal of $BaTiO_3$ with a small-signal reflectivity of 25), an intracavity hologram of two superimposed gratings, and two output couplers normal to each of the diffracted beams. The resonator could be made to oscillate between the conjugator and either output coupler by adjusting the loss in either path. The loss in either leg, introduced to simulate threshold behavior, was changed by placing neutral-density filters between the output coupler and the hologram. By measuring the power in each leg it was determined that in steady state only one leg oscillated at a time. This can be explained by the fact that in the conjugator the two resonator modes overlap physically and are competing for the same gain region. Therefore the mode with less loss builds in amplitude at the expense of the other. In additional experiments we have operated a double-PCM resonator by replacing mirror 1 shown in Fig. 4 by a second PCM.

An all-optical associative memory employing a hologram in an optical cavity utilizing PCM's has been described and initial experimental results presented. The PCM's provided nonlinear feedback, thresholding, and gain, improving the selectivity and stability of the memory. The reconstruction of an object from a partial input was demonstrated. Using simple plane-wave objects, we have shown that, by adjusting the threshold, either one or both objects could be made to build up in the PCM cavity, demonstrating that the memory is nonlinear and selective. The recording medium could be replaced with real-time media such as photorefractive crystals. Thicker recording media have the added advantage of higher angular selectivity, thus permitting greater discrimination between images and storage of a larger data base.

We thank C. DeAnda for technical assistance and T. O'Meara, D. Pepper, D. Psaltis, and G. Valley for helpful discussions.

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We have in this period demonstrated associative recall from a partial image which has a large gray-scale range. We have also demonstrated associative recall with two separate images stored in the hologram. In addition we have made a preliminary study of the analogy of our method and model to that of Hopfield, comparing and contrasting the two. The technical details of these studies are described in the reprints of the several presentations on this subject we have given and their abstracts are produced here.

OSA Annual Meeting, Washington, October 1985

All Optical Associative Holographic Memory with Feedback Using Phase Conjugate Mirrors

by

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ABSTRACT

An associative holographic memory utilizing phase conjugate mirrors as a nonlinear feedback mechnism is described. Addressing the system by a partial or distorted version of the stored data generates the complete version most closely associated with that input.

All Optical Associative Holographic Memory with Feedback Using Phase Conjugate Mirrors

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SUMMARY

We propose to use a hologram as a storage medium in an all optical feedback configuration which includes phase conjugate mirrors. The associative properties of holograms have been suggested earlier by Gabor. Addressing the system by a partial or distorted version of the stored data generates the complete version most closely associated with that input. The phase conjugate mirrors are used to form an optical resonator, containing the hologram, with threshold adjustment such that only the strongest reconstructed image and its corresponding reference beam are fully reconstructed.

Because a hologram can be decomposed into a set of single holographic gratings, we demonstrated that a PCR (phase conjugate resonator) can operate with multiple intracavity gratings. The resonator consisted of the phase conjugator, $BaTiO_3$, an intracavity hologram of two superimposed gratings and two output couplers normal to each diffracted beam. The resonator oscillates between both output couplers unless there is a different loss in each path. By adjusting the loss and therefore, the threshold, either leg of the resonator could be made to oscillate.

To replace permanent holograms, the use of photorefractive materials for real-time adaptive associative memories will also be presented.

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Optical holographic associative memory using a phase conjugate resonator

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Optical Holographic Associative Memory Using a Phase Conjugate Resonator

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Abstract

An all-optical fully parallel associative memory system is described which utilizes a holographic data base. Phase conjugate mirrors are used to provide feedback, thresholding, and gain. The memory is compared to the Hopfield neural network model of associative memory and preliminary experimental results are presented.

Introduction

A large body of research work in the area of neural network modeling has demonstrated the feasibility of associative memories based on systems of distributed and interconnected memory elements with nonlinear feedback.[1,2] Such associative memories have several useful properties such as reconstruction of an output from a partial input, heteroassociation, and relative insensitivity to damage or modification of the individual memory elements since data are stored globally over all the elements rather than locally. The self-organizing properties of randomly interconnected neural networks with connectivity and nonlinear feedback have been suggested for information processing applications such as pattern recognition, image understanding, and robotic vision. The ability to reconstruct a complete stored data sequence from a partial or distorted input "key" may have application in rotation or scale invariant image processing.

A recent neural network model suggested by Hopfield[2] has been implemented optically.[3] Optics is especially well suited to implementation of such distributed associative memories because of the large degree of parallelism and interconnection capability. Nonlinear thresholding, necessary for the associative behavior of the Hopfield model, was implemented optoelectronically in Ref. 3.

Close examination of the Hopfield model shows that it is analogous in many respects to holography, which in itself has been utilized as an associative memory.[4] Input binary data vectors are multiplied by an association matrix, T_{ij}, which is formed from all the stored vectors. This matrix represents a linear transformation and is analogous to the diffraction of wavefronts involved in recording and reading an optical hologram. It will be shown below that the T_{ij} transformation is similar to the cascaded correlation and convolution operations involved in reconstructing a wavefront in conventional holography. The additional features of the Hopfield model which are lacking in conventional holography are multiple iterations, feedback, and thresholding. These features improve the signal-to-noise ratio and tend to force the output to one of the stored states. The nonlinearity of an associative memory is a key advantage over a simple correlator. It allows the quantization of intermediate results when several stages are cascaded. The quantization of intermediate results has been shown to greatly improve the net signal-to-noise ratio of cascaded systems.[4]

Holography has potential advantages over optoelectronic implementations of associative memories because of its high information storage capacity and an ability to store three-dimensional wavefronts, including both amplitude and phase information. In the following sections we discuss the similarities and differences between holography and the Hopfield model. In addition, it will be shown that nonlinear thresholding, iterative behavior, feedback, and gain can be added to a holographic memory by placing the hologram in an optical cavity formed by two phase conjugate mirrors (PCMs). Such a configuration combines the advantages of holography (full all-optical parallelism and high information capacity) with the nonlinear error correction properties of associative neural nets such as the Hopfield model.

Analogies between holography and the Hopfield model

In the Hopfield model, M binary vectors, $v^{(m)}$, which are N bits long are stored in a matrix, T_{ij}, defined as follows:

$$T_{ij} = \sum_{m}^{M} (2v_i^{(m)} - 1)(2v_j^{(m)} - 1) \quad \text{if } i \neq j, \text{ 0 otherwise}$$

The vector components, $v_i^{(m)}$, assume values of 1 or 0, and the corresponding stored components $(2v_i^{(m)}-1)$ assume values of 1 or -1. If T_{ij} is multiplied by an input which is a partial or distorted version, $\hat{v}^{(m0)}$, of one of the stored binary vectors, the bit, $\overset{o}{v}_i^{(m0)}$, is an estimate of the stored bit $(2v_i^{(m0)}-1)$:

$$\overset{o}{v}_i^{(m0)} = \sum_j T_{ij}\hat{v}_j^{(m0)}$$

$$= (2v_i^{(m0)}-1)\sum_{j\neq i}(2v_j^{(m0)}-1)\hat{v}_j^{(m0)}$$

$$+ \sum_{j\neq i}\sum_{m\neq m0}(2v_i^{(m)}-1)(2v_j^{(m)}-1)\hat{v}_j^{(m0)}$$

$$= (N_a - N_b)(2v_i^{(m0)}-1) + \sum_{m\neq m0}(2v_i^{(m)}-1)\left[\sum_{j\neq i}(2v_j^{(m)}-1)\hat{v}_j^{(m0)}\right],$$

where N_a is the number of 1s in $\hat{v}^{(m0)}$ which match $v^{(m0)}$, and N_b is the number of 1s which do not match. A thresholding operation on $\overset{o}{v}^{(m0)}$ improves the signal-to-noise ratio. The first term of the above equation is the desired stored vector which has the largest inner product or "correlation" with the input vector. This is analogous to holography in which it can be shown that the input wavefront is correlated with the stored wavefronts and the result convolved with the corresponding output wavefronts.[5] As in holography, the correlation value is dependent on the form of the stored data, although in different ways. In particular, the factor N_a-N_b multiplying the desired vector is not dependent solely on the Hamming distance of the input vector from the stored vectors, but is also dependent on the number and distribution of 1s in the data. For example, if the stored vector is 11110000 and the input word is 11111111, the Hamming distance is 4 but the "correlation value" N_a-N_b is 0.

An interesting feature of the Hopfield model is that the complement of a stored vector is also an eigenvector of the system. Note that for an original stored vector N_a is large and N_b is zero, while for its complement N_a is zero and N_b is large and equal to the N_a value for the original vector. Both the stored vector and its complement maximize the absolute value of N_a-N_b and thus are eigenvectors (stable states) of the system. The analogue in holography is that if the wavefront A reconstructs B, then by invoking Babinet's principle it can be shown that 1-A, the complement of A, will reconstruct 1-B, the complement of B.

If the diagonal terms T_{ii} of the association matrix are not set equal to 0, a third term appears in the last equation which is a reproduction of the partial input vector. This term is analogous to the zero order term in holography which leaves the addressing beam undeflected and multiplied by the autocorrelations of all stored images and reference beams. In the Gabor-type on-axis holograms, the zero order term is superimposed on the image itself thus degrading its discernability. This confounding superposition would have occured in the Hopfield model as well if the diagonal terms had not been eliminated.

The Hopfield model can also be adapted for heteroassociation by suitably modifying the T_{ij} matrix. In heteroassociation an input vector recalls a completely different stored vector. The corresponding heteroassociative properties of holography are well known and routinely utilized.[5]

The second term in the last line of the last equation represents noise from the correlation of the input vector with the undesired stored vectors. The mean and variance of the output can be easily calculated and related to the signal-to-noise ratio before thresholding. If it is assumed that the vector components are statistically independent and the number of 1s in the stored vectors is approximately equal to the number of 0s (expectation value of T_{ij} is 0), then the mean and variance are given by

$$\eta_i = E\{\overset{o}{v}_i^{(m0)}\} = (N_a - N_b)(2v_i^{(m0)}-1)$$

$$\sigma_i^2 = E\{(\overset{o}{v}_i^{(m0)} - \eta_i)^2\}$$

$$= E\left\{\sum_{\substack{m\neq m0 \\ m'\neq m0 \\ j\neq i \\ j'\neq i}}(2v_i^{(m)}-1)(2v_i^{(m')}-1)(2v_j^{(m)}-1)(2v_{j'}^{(m')}-1)\hat{v}_j^{(m0)}\hat{v}_{j'}^{(m0)}\right\}$$

Because of the assumed statistical independence of the vector components, all of the terms vanish except for m=m' and j=j' so that

$$\sigma^2 = E\left[\sum_{\substack{m \neq m0 \\ j \neq i}} (2v_i^{(m)}-1)^2 (2v_j^{(m)}-1)^2 \, (\hat{v}_j^{(m0)})^2 \right]$$

$$= (M-1)(N_a + N_b)$$

where E denotes expectation value and (N_a+N_b) is the mean number of 1s in $\hat{v}^{(m0)}$. The variance is independent of bit position i. The signal-to-noise ratio before thresholding (which is the same for each of the N bits of the recalled vector) is given by

$$SNR = \frac{\mu_i}{\sigma} = \frac{N_a - N_b}{\sqrt{(M-1)(N_a + N_b)}} \quad .$$

The above result reduces to that in Ref. 2 if $N_a = N/2$ and $N_b=0$. This, however, may not always be a good assumption. If the stored data are nonrandom and there is some correlation between components of the stored vectors (expectation value of T_{ij} not equal to 0), then the mean value of the output is given by

$$\mu_i = (N_a - N_b)(2v_i^{(m0)}-1) + \sum_{m \neq m0} \sum_{j \neq i} f_{i-j}^{(m)} \, \hat{v}_j^{(m0)}$$

$$= (N_a - N_b)(2v_i^{(m0)}-1) + (M-1) \sum_{j \neq i} f_{i-j} \, \hat{v}_j^{(m0)} \quad ,$$

where f_{i} is given by

$$f_{i-j}^{(m)} = E\left[(2v_i^{(m)}-1)(2v_j^{(m)}-1)\right] \quad ,$$

and is a measure of the statistical correlation of pairs of bits within a vector (assumed in the interest of simplicity to be the same for all stored vectors) as a function of their separation, i. Statistical correlation between neighboring bits results in a nonzero f_i. Thus for "nonrandom" data a new error term appears which is the input vector convolved with f_i. A corresponding expression can also be calculated for the variance which includes the effects of statistical correlation between neighboring bits

$$\sigma^2 = (M-1)(N_a + N_b) + \frac{1}{4}(M^2 - 3M + 3) \sum_{\substack{j \neq j', i \\ j' \neq j, i}} f_{i-j} f_{i-j'} f_{j-j'}$$

$$+ \frac{1}{4}(M^2 - M) \sum_{\substack{j \neq j', i \\ j' \neq i}} f_{i-j} f_{i-j'} \quad .$$

The variance is again independent of bit position i because we have assumed that f_{ij} is a function of separation i-j only and not position. The variance is increased by a large amount (and the signal-to-noise ratio decreased) by such statistical correlation. The performance of the Hopfield model is therefore very dependent on the randomness of the stored data. In some applications such as image storage strong statistical correlations will exist between the components of stored vectors. In such cases it would be necessary to utilize a "randomizing" transformation of the data in order to use the Hopfield model. This is again analogous to holography in which the quality of reconstruction is improved by using images with a sharp autocorrelation peak and uniform cross-correlation functions. Diffusers are often used in holographic systems to randomize the wavefront at the hologram and improve the reconstruction quality.[5]

A difficulty with transferring the Hopfield model directly into the optical domain is its relative storage inefficiency. M is limited to approximately 0.15 N for one-dimensional vectors.[2] In addition, storing two-dimensional images requires a four-dimensional matrix, T_{ij}. Implementing the necessary matrix-matrix multiplication is awkward using spatial light modulators or film.[3] An alternate approach is to combine holography, which was shown above to exhibit many of the essential features of an associative memory, with a mechanism to provide the additional iterative capability, feedback, and thresholding features of neural network models. Phase conjugation, in particular four wave mixing in photorefractive crystals, is such a mechanism and will be described in the next sections.

Holographic phase conjugate associative memory

An implementation of a nonlinear associative memory based on a hologram situated in a cavity formed by two phase conjugate mirrors (PCMs) is illustrated in Figure 1. Unlike another proposal for a nonlinear holographic associative memory,[6] our implementation requires only a single hologram which is simultaneously addressed by the input wavefront and by reconstructed object and reference wavefronts which were used in recording the hologram. PCMs are used for beam retroreflection, gain, and thresholding. This provides the necessary nonlinearity which favors the strongly correlated signals and forces the system toward a stable state. The use of PCMs also results in the automatic self alignment of the object and reference wavefronts with respect to the hologram, eliminating some of the critical alignments necessary in the two hologram approach.

The memory consists of a hologram in which a stored object, a , is written using a plane wave reference, b , as illustrated in Figure 1. Multiple objects are written sequentially onto the hologram, each associated with a different angularly separated plane wave reference. The two legs of the memory consist of a reference leg and an object leg, each with its respective PCM. A partial or distorted input object, ã , generates distorted reference beams, (b̃). The wavefront b̃ is focused by the lens into PCM 1. PCM 1 has a threshold for conjugation and may, for example, be a self pumped photorefractive crystal or a stimulated Brillouin scattering cell. Since PCM 1 is in the Fourier plane of the lens, the desired plane wave reference component of b̃ forms a bright spot on PCM 1, which in turn will threshold and conjugate the desired plane wave reference back toward the hologram as a partially restored conjugated reference, b̄ . This partially restored reference then illuminates the hologram and generates a partially restored object, ā , which is conjugated by PCM 2 back to the hologram. PCM 2 does not threshold the object beam and may consist of an externally pumped photorefractive crystal. The round trip is then completed and the cycle repeats with an improvement in the associated output. This proceeds at a rate governed by the PCM cavity response time. If the combined gain of the PCMs is comparable to the losses in the cavity, oscillating wavefronts will build up which correspond to real and virtual images of the stored object having the largest correlation with the input object.

One advantage of this type of nonlinear associative memory over the Hopfield model is that thresholding is done on the reference beam rather than the object beam. The output, therefore, can be a two dimensional gray-scale image undistorted by the thresholding process. Alternatively, thresholding can be performed on the object beam instead if recall of two-dimensional binary images is desired. The memory is then more closely analogous to the Hopfield model. The memory can also be used for heteroassociation in which a partial input object recalls a complete version of a different object. For thresholding non-plane wave references the lens in Figure 1 should image the reference onto PCM 1 so that spatial thresholding can be performed. The resolution of the system will then be limited by crosstalk between pixels at the PCM.

The object and reference legs are self aligning with respect to the hologram because of the PCMs. An alignment requirement exists, however, between the input a and the hologram. The translational alignment accuracy required can be reduced by utilizing a Fourier transform hologram.

Two regimes of operation are possible for this associative memory as the combined gain of the PCMs is increased. If the PCM gain is less than the cavity losses, then the memory operates as a Fabry-Perot cavity with the hologram determining the amplitude distribution. Referring to Figure 2, the following equation must be satisfied for self consistency of the oscillating wavefronts in the cavity

$$C_{\tilde a}\,\tilde a(z_1) = t\alpha^2 R_1 R_2 \; [illegible]$$

where a and b are the recorded object and reference wavefronts. The hologram transmittance is given by α a·b*, ã is the partial input wavefront, $C_{\tilde a}$ and [illegible] are complex scalar coefficients which describe the amplitudes of the partial and reconstructed wavefronts respectively. R_1 and R_2 are complex reflection coefficients of PCM 1 and PCM 2, and t is the beamsplitter transmittance. The longitudinal coordinates, z_1 and z_2, [illegible] propagation path define planes as shown in Figure 2. The parameter α is a measure of the hologram's diffraction efficiency. If it is assumed that a and b represent [illegible] objects with rapidly varying phase variations, or if diffusers are used [illegible] the objects, then at the hologram plane, a^2 and b^2 are approximately constant [illegible] be normalized to 1. The above equation can then be solved for the reconstructed [illegible] [illegible] in terms of the input $C_{\tilde a}$.

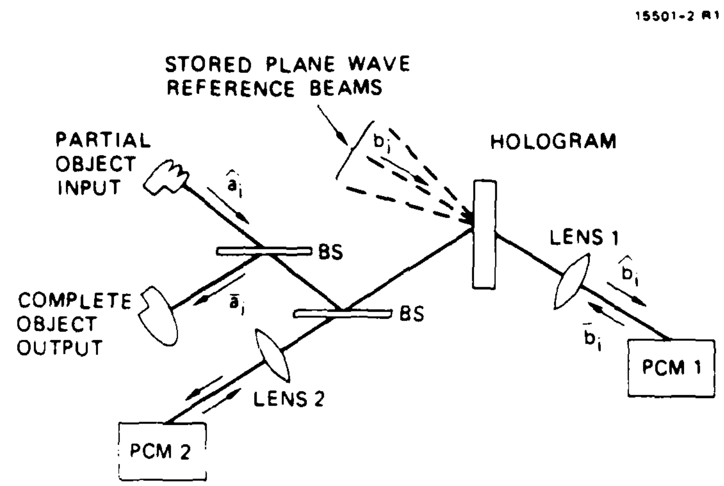


Figure 1. Holographic phase conjugate nonlinear associative memory

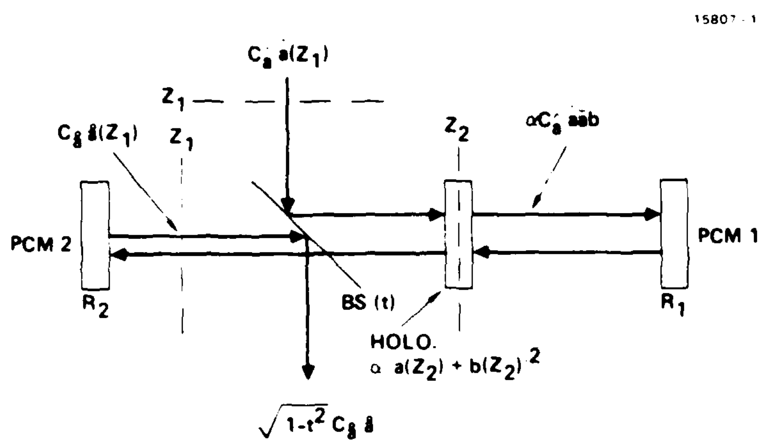


Figure 2. Propagating wavefronts in the cavity

$$\text{output} = \sqrt{1-t^2}\, C_{\hat{a}} = \frac{1-t^2}{t} \frac{\xi}{1-\xi} C_a$$

where $\xi = t^2\alpha^2 R_1 R_2$. In the regime for which the above equation is valid, ξ must be less than 1, and pump depletion effects in the PCMs are assumed negligible. Both the hologram and the thresholding PCM contribute to the selectivity of the memory. The hologram implements a linear selectivity described by a correlation of the input with the stored wavefronts. The resultant correlation peak is convolved with the respective stored reference wavefronts. The cross terms of the correlation convolution are reduced relative to the main peak by the thresholding PCM with a resultant improvement in signal-to-noise ratio. In addition, the memory can exhibit gain if the quantities t, α, R_1, and R_2 are selected properly.

The other regime of operation is one in which the combined gain of the PCMs exceeds the cavity losses, e.g., $t^2\alpha^2 R_1 R_2$ is greater than 1. In this regime all of the stored wavefronts are above the threshold for oscillation, assuming that the hologram diffraction efficiency is approximately the same for all stored wavefronts. Thus in the steady state all stored objects will be read out without regard to the input, an undesirable situation for an associative memory. Therefore, either readout must be performed on time scales comparable to the cavity response time (before steady state is reached), or means must be provided for modification of the gain by the input. For example, a two-wave mixing photorefractive crystal operated in the counterpropagating mode[8] and located in the reference arm as shown in Figure 3, would impart a larger gain to the stronger reference component. By proper orientation of the crystal, the reference component propagating toward PCM 1 acts as a pump for the conjugated reference component propagating back toward the hologram. Since the two counterpropagating reference components are conjugates of each other, their overlap in the crystal is maximized, which enhances energy transfer between them. Therefore, the strongest reference will have the largest gain, and its associated stored object will be favored to oscillate. Alternatively, the two-wave mixing crystal could be located in the object arm, but in this case the readout object may be distorted.

The holographic phase conjugate associative memory can have gain in that the output amplitude can be greater than the input. Therefore, it may be possible that several such units can be cascaded or fanned out to form more complicated "trees" for higher order computing such as symbolic manipulation. The error correcting capability of nonlinear associative memories is necessary for such structures.

Experimental results

Our experimental arrangement (Figure 4) was a single-pass, noniterative system consisting of the hologram and a phase conjugate mirror. The hologram was part of a Newport Corporation thermoplastic holographic camera. The phase conjugate mirror was produced by degenerate four wave mixing in the photorefractive crystal $BaTiO_3$. The hologram was generated by recording the interference of an object beam, a single transparency consisting of four geometrical shapes in contact with a diffuser (Figure 5(a)), and a spherical diverging reference beam. Upon illumination of the hologram by the object beam (or part of it), the diffracted beam propagating in the original direction of the reference beam becomes the probe beam for a degenerate four wave mixing (DFWM) system. The signal generated by DFWM is the phase conjugate of the probe. It propagates back toward the hologram and recreates the object beam. This recreated object beam has all of the information originally contained in the input image. Therefore, by using a partial input, one of the geometric shapes (Figure 5(b)) and the entire object image of four shapes was regenerated (Figure 5(c)). As expected, the system did not reconstruct the object image when the input object was translated from the original position at which the hologram was recorded. This verified that the complete output object was generated by the incomplete input object and not by a stray beam. High resolution grayscale images have also been reconstructed using this system.

In one implementation of the associative memory multiple objects are stored using angular multiplexing of plane wave reference beams. As a first step toward multiple object storage, we demonstrated in another series of experiments that a phase conjugate resonator cavity can operate with a hologram formed with multiple plane wave objects. Plane waves were used to form gratings in a dichromated gelatin hologram of approximately 60% diffraction efficiency. The resonator, shown in Figure 6, consisted of the PCM (externally pumped $BaTiO_3$), an intracavity hologram of two superimposed gratings, and two output couplers normal to each of the diffracted beams. The reflectivity of the PCM was large enough to overcome the optical losses so operation was in the regime where $t^2\alpha^2R_1R_2$ is greater than 1. The resonator could be made to oscillate between the PCM and either output coupler by adjusting the loss in either path. (The loss was modified by placing neutral density filters between the output coupler and the hologram.) This simulated the effects of modifying the gain according to the input, as discussed above.

It was determined that in steady state only one leg oscillated at a time. In the PCM the two resonator modes overlap spatially and are competing for the same gain. Therefore the mode with the least loss [illegible] in amplitude at the expense of the other. [illegible] operated a cavity with two PCMs by replacing mirror 1 in Figure [illegible] PCM.

Summary

An all optical nonlinear associative memory utilizing a [illegible] formed by phase conjugate mirrors has been described and its relation to the [illegible] neural network model discussed. It has been shown that phase conjugate mirrors [illegible] the nonlinear feedback and thresholding characteristics which are features of the [illegible] model. The experimental reconstruction of an image from a partial input was demonstrated using a single pass non-iterative system. Using [illegible] "images" [illegible] hologram, we have shown that by adjusting the losses, either [illegible] images [illegible] to oscillate in the cavity [illegible] The thermoplastic hologram [illegible] photorefractive crystals. This [illegible] make real time [illegible] a necessary prerequisite for [illegible] learning behavior [illegible] the system.

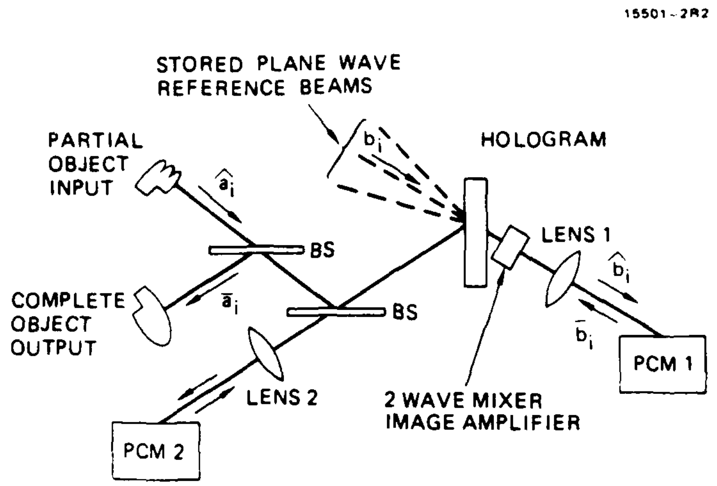


Figure 3. Gain modification using counter-propagation in a two-wave mixing crystal.

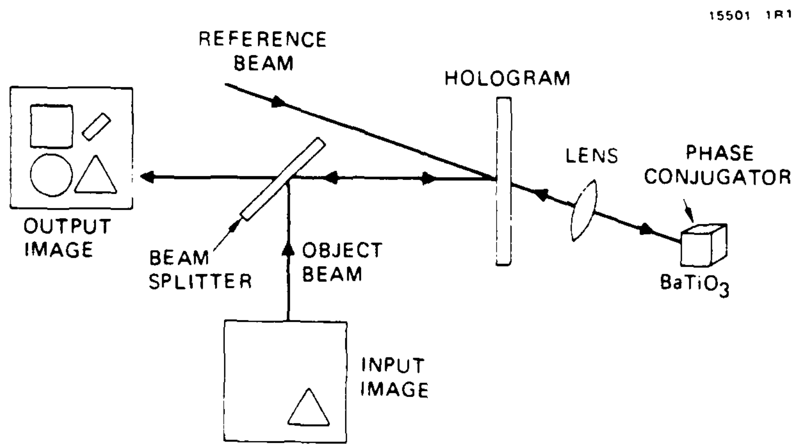
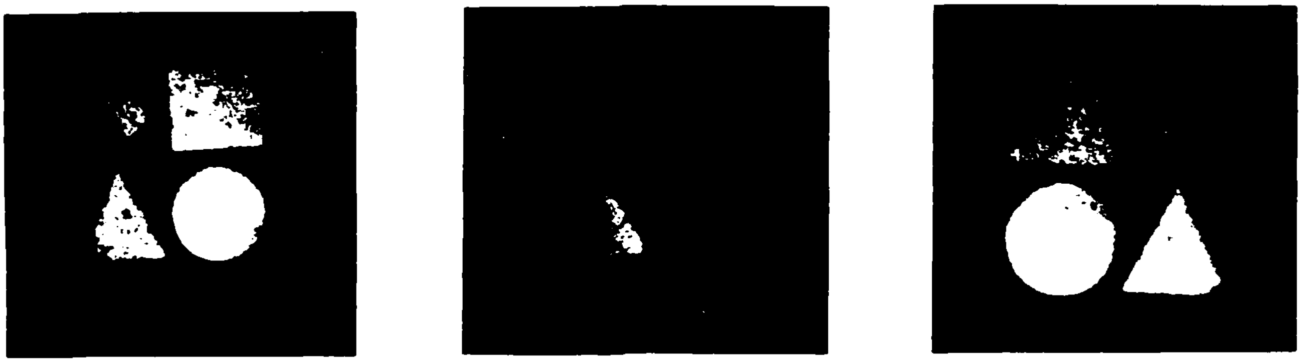
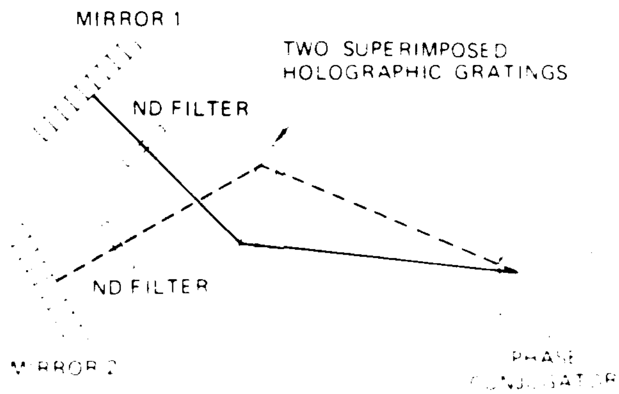


Figure 4. Schematic of an experiment which demonstrated the complete image reconstruction from a partial input



A B C

Figure 5. Experimental results. A: image stored in memory. B: incomplete input image. [illegible] associated output image reflected by mirror.



[illegible]

Acknowledgments

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ASSOCIATIVE HOLOGRAPHIC MEMORY WITH FEEDBACK USING PHASE CONJUGATE MIRRORS

Invited Paper

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Abstract

Associative recall of grayscale holographic images with gain and selectivity is demonstrated using phase conjugate mirrors for thresholding and feedback. Analysis is presented for both device and resonator cavity thresholding.

ASSOCIATIVE HOLOGRAPHIC MEMORY WITH FEEDBACK

USING PHASE CONJUGATE MIRRORS

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Background:

Associative memories and associative processing have many applications in symbolic and parallel computing.[1] Optical schemes, in particular those based on holographic principles, are well suited to associative processing because of their high parallelism and storage capacity. Previous workers[2] have demonstrated that holographically stored images can be recalled using relatively complicated reference images. In this paper we describe the use of phase conjugate mirrors (PCM's) to improve the selectivity and performance of a holographic associative memory by introducing gain, feedback, and thresholding.

Associative properties of holograms

The formation of a hologram involves the exposure of a light sensitive medium with two coherent wave amplitudes $A(u,v)$ and $B(u,v)$ generated by two objects a and b. When irradiated by a complex wavefront $A_d(u,v)$, which is a distorted or incomplete version of $A(u,v)$, the amplitude after the hologram is given by:

$$A_d|A+B|^2 = A_d(|A|^2 + |B|^2) + A_dAB^* + A_dA^*B \qquad (1)$$

The last term of this expression represents the convolution of the object b with the correlation of a_d and a. For most natural objects there is sufficient phase variation so that if a_d is identical, or close, to a, their correlation provides a sharp peak and b is faithfully reconstructed.

Multiple objects b_i can be stored in a hologram, each associated with a different reference wave a_i. This by itself acts as a linear associative memory, so that a distorted a_{di} can be represented as a weighted superposition of several a_j, without discrimination. To display only the object b_i most closely associated with a_{di}, thresholding is required to pass only $a_{di}a_i^*b_i$. Another useful application of an associative memory is the generation of a complete stored object a from a partial version of the object, a_d. It can be shown that if the last term in Eq (1) is used to readdress the hologram, a complete version of a is generated. In the next section it will be shown that

PCM's can be used for the readdressing function and in addition provide gain for cascading associative modules and thresholding to improve the selectivity.

Holographic implementation of an associative memory utilizing phase conjugate mirrors.

The memory consists of a hologram in which a stored object, a_i, is written using a plane wave reference b_i, as illustrated in Figure 1. The two legs of the memory consist of a reference leg and an object leg, each with its respective PCM. The two PCM's form a phase conjugate resonator cavity with the hologram determining the transverse mode structure. A partial or distorted input object a_{di} generates a distorted reference beam b_{di}. The distorted reference b_{di} is focused by the lens onto PCM 1. PCM 1 is a thresholding conjugator, e.g. SBS or self pumped photo refractor. PCM 1 thresholds b_{di}, conjugates, and reflects it back toward the hologram as a partially restored reference b_i. This partially restored reference then illuminates the hologram and generates a partially restored object a_i which is conjugated and reflected by PCM 2 back to the hologram (without thresholding). If the initial gain exceeds the losses, the system will oscillate as a resonator. The restoration proceeds at a rate governe. by the phase conjugate resonator response time. If a fixed hologram is used, many objects can be stored in the hologram by using different reference waves during recording. The memory will then select the stored object having the largest correlation with the input object.

In the above system the net gains are approximately equal for all the stored objects. Discrimination is accomplished by utilizing the threshold characteristics of the PCM. It is also possible to discriminate between stored objects by modifying the gain for a particular object according to the input and utilizing the cavity threshold for oscillation.

A possible variation of the system would be to use a spatially modulated reference beam in the formation of the hologram. For example, the stored object a_i could serve as its own reference beam by employing a beam splitter in the proper location. Furthermore, a different object could serve as a reference, resulting in a hetero-associative memory.

Experimental results

We have demonstrated in preliminary experiments the total reconstruction of an image when only a partial image addressed the system. This was done in the single pass configuration shown in Figure 2, which consisted of a single image hologram, acting as the memory element, and a non thresholding phase conjugate mirror. The hologram was recorded at 5145Å using a Newport

Corporation thermoplastic holographic camera. The phase conjugate mirror was produced by degenerate four wave mixing in the photorefractive crystal $BaTiO_3$. The hologram was generated by recording the interference of an object beam, (a transparency of four geometrical shapes Figure 3A), and a spherical diverging reference beam at the hologram plane. Upon illumination of the hologram by the object beam, or part of it, the diffracted beam propagating in the original direction of the reference beam becomes the probe beam for a degenerate four wave mixing (DFWM) system. The signal generated by DFWM is the phase conjugate of the probe, i.e. the reference beam propagating in reverse. When the DFWM signal illuminates the hologram a portion of it is diffracted, recreating the object beam. Thus, using the input of a partial object image (Figure 3B), merely one of the four geometrical shapes, the entire object image of four shapes was regenerated (Figure 3C). As expected, the system did not reconstruct the object image when the input object was translated from the original position at which the hologram was recorded. This verifies that the complete output object was indeed generated by the incomplete input object and not by any other beam. Grayscale images with good detail have also been reconstructed with this system.

Conclusions

An all optical associative memory employing a hologram in an optical cavity utilizing phase conjugate mirrors has been described and initial experimental results presented. The phase conjugate mirrors provided nonlinear feedback, thresholding, and gain, improving the selectivity and stability of the memory and allowing cascading of such associative modules. The reconstruction of an object from a partial input was demonstrated.

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Fig. 1. Implementation of an associative holographic memory using phase conjugate mirrors.

Fig. 2. Experiment which demonstrated the complete object image reconstruction from a partial input image.

Fig. 3. Experimental results: (A) image stored in memory; (B) partial input image; (C) associated output

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SUMMARY

ASSOCIATIVE MEMORY IN A PHASE CONJUGATE RESONATOR CAVITY UTILIZING A HOLOGRAM

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An all-optical fully parallel associative memory system is described which utilizes a holographic data base. Phase conjugate mirrors are used to provide feedback, thresholding and memory. Preliminary experimental results are presented.

A large body of research work in the area of neural network modeling has demonstrated the feasibility of associative memories based on systems of distributed and interconnected memory elements with nonlinear feedback. Such associative memories have several useful properties including the reconstruction of an output from a partial input, heteroassociation, and relative insensitivity to damage or modification of the individual memory elements since data are stored globally over all the elements rather than locally. The self-organizing properties of randomly interconnected neural networks with connectivity and nonlinear feedback have been suggested for information processing applications such as pattern recognition, image understanding, and robotic vision. The ability to reconstruct a complete stored data sequence from a partial or distorted input "key" may have application in rotation or scale invariant image processing.

Close examination of the Hopfield model shows that it is analogous in many respects to holography, which in itself has been utilized as an associative memory. Input binary data vectors are multiplied by an association matrix which is formed from all the stored vectors. This matrix represents a linear transformation and is analogous to the diffraction of wavefronts involved in recording and reading an optical hologram. We show that this transformation is similar to the cascaded correlation and convolution operations involved in reconstructing a wavefront in conventional holography. The additional features of the Hopfield model which are lacking in conventional holography are multiple iterations, feedback, and thresholding. These features improve the signal-to-noise ratio and tend to force the output to one of the stored states. The nonlinearity of an associative memory is a key advantage over a simple correlator. It allows the quantization of intermediate results when several stages are cascaded. The quantization of intermediate results greatly improves the net signal-to-noise ratio of cascaded systems.

Holography has potential advantages over optoelectronic implementations of associative memories because of its high information storage capacity and an ability to store three-dimensional wavefronts, including both amplitude and phase information. We discuss the similarities and differences between holography and the Hopfield model. In addition, we show that nonlinear thresholding, iterative behavior, feedback, and gain can be added to a holographic memory by placing the hologram in an optical cavity formed by two phase conjugate mirrors (PCMs). Such a configuration combines the advantages of holography (full all-optical parallelism and high information capacity) with the nonlinear error correction properties of associative neural nets such as the Hopfield model. The use of real time adaptable memory employing photorefractive crystals is also discussed.

We have demonstrated two key features of an all optical associative memory. First we have reconstructed a complete 2-dimensional gray scale image from a partial input, and second we stored a pair of 2-dimensional images and reconstructed either complete image from its associated partial input. We use a hologram as a memory element in an optical feedback configuration which utilizes phase conjugate mirrors. A holographic memory is used because multiple gray scale images with large space bandwidth products can be stored by use of angular multiplexing. In addition the information is stored globally, and is processed rapidly in parallel. Phase conjugate mirrors are used to provide regenerative feedback, optical gain, and thresholding. In one set of experiments we stored a 2-dimensional gray scale image of a person's face. We were able to recall the entire face by addressing the system with merely a portion of the face. In another set of experiments designed to demonstrate the system's selectivity for multiple stored objects, we stored the two words OPTIC and WAVES. When a portion of either word was input to the system, for example the W, the entire word WAVES would appear at the output suppressing the word OPTIC. Conversely when merely a single letter of the word OPTIC addressed the system, the complete word was produced at the output.

San Francisco, CLEO, June 1986

ALL OPTICAL ASSOCIATIVE MEMORY INCORPORATING HOLOGRAPHY AND PHASE CONJUGATION

by

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ABSTRACT

An all optical associative memory which incorporates holography and phase conjugation is described. We present experimental results which have reconstructed 2-D images with grey scale and high spatial frequencies when only a partial image was input into the system.

TALK FOR CLEO 1986

by

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SUMMARY

We have demonstrated an all optical implementation of an associative memory. An associative memory is a device which when addressed by a partial, noisy or distorted version of the stored data generates the complete version most closely associated with that input. We have used a hologram as a storage medium in an optical feedback configuration which incorporates phase conjugate mirrors. The hologram is capable of storing multiple images and we exploit its inherent associative property. Furthermore the information is stored globally and is well suited to parallel processing. The phase conjugate mirrors are used to provide regenerative feedback, optical gain and thresholding. We have stored a 2-D image with grey scale and high spatial frequencies and have been able to reconstruct the entire image by inputing just a portion of the stored image. In additional experiments we have demonstrated the system selectivity when multiple plane wave objects were stored in memory. By using a resonator configuration and simulating threshold behavior the system was able to select and reconstruct the desired stored object.

The static recording medium used in our experiments could be replaced with real time recording medium. This would allow the

stored data to be updated or changed based upon the output. We will discuss the possible applications of the device in various areas of artificial intelligence, that is symbolic processing and computation. We will present schemes which exhibit logical decision making and image classification.

Proceedings SPIE Vol. 684, San Diego, August 1986

Holographic Associative Memory Employing Phase Conjugation*

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Abstract

The principle of information retrieval by association has been suggested as a basis for parallel computing and as the process by which human memory functions.[1] Various associative processors have been proposed that use electronic or optical means. Optical schemes,[2-7] in particular, those based on holographic principles,[3,6] are well suited to associative processing because of their high parallelism and information throughput. Previous workers[8] demonstrated that holographically stored images can be recalled by using relatively complicated reference images but did not utilize nonlinear feedback to reduce the large cross talk that results when multiple objects are stored and a partial or distorted input is used for retrieval. These earlier approaches were limited in their ability to reconstruct the output object faithfully from a partial input.

Introduction

We will combine the principles of holographic memories and phase conjugation to implement a novel, all-optical holographic associative memory and symbolic processor. An associative memory performs image retrieval when partial or noisy image data are input to the device. The memory, a hologram, is capable of globally storing multiple three-dimensional (3-D) objects. To improve device performance, a nonlinear interaction is obtained by using phase conjugate mirrors (PCMs) which provide retroreflection, regenerative feedback, thresholding, and amplification. (See Ref. 9 for a detailed discussion.) By utilizing real-time holography, learning can be realized.

We have demonstrated an associative memory capable of retrieving up to two stored images from memory. This has been achieved by using the properties of phase conjugation: gain, threshold, and wavefront reversal. PCMs provide the necessary nonlinearity to favor the strongest correlation between the partial or noisy input data and the associated data stored in the hologram.

As shown schematically in Figure 1, a single hologram is simultaneously addressed by the object and conjugate reference beams, the latter acting as the key that unlocks the associated information. The memory consists of a hologram in which a stored object, a, is written using a plane wave reference, b. The two legs of the memory consist of a reference leg to the left of the hologram and an object leg to the right of the hologram. Each leg has its respective PCM. A partial or distorted input object, â, generates a distorted reference beam b. This distorted reference beam is focused by the lens onto a thresholding conjugator, PCM 1. The desired plane wave reference component becomes the input to PCM 1. PCM 1 will threshold this input beam, then conjugate, and reflect it back toward the hologram as a partially restored reference, b*. This partially restored reference then addresses the hologram and generates a partially restored object. The object beam is conjugated and reflected by PCM 2 back to the hologram (without thresholding). Thresholding is not done in this leg because desirable information would be lost if the image contained gray-scale information. The round trip is then completed and the cycle repeats. The image restoration proceeds at a rate governed by the phase conjugate resonator response time.

If the combination of PCM 1 and PCM 2 has gain comparable to the losses in the system, the output will converge to a real image of the complete stored object. By using a hologram, many objects can be stored in the hologram by using different reference waves. The memory will then select the stored object having the largest correlation with the input object. The object and reference legs are self-aligning with respect to the hologram because of their phase conjugate nature. There is an alignment requirement, however, between the partial input and the stored hologram. The translational alignment accuracy required can be reduced by utilizing a Fraunhofer (Fourier transform) hologram. A possible variation of the system would be to use a spatially modulated reference beam in the formation of the hologram. For example, an object could serve as its own reference beam by employing a beamsplitter in the proper location. Furthermore, a different object could serve as a reference resulting in a heteroassociative memory.

* Presented at the International Optical Computing Conference, Jerusalem, Israel, July 1986

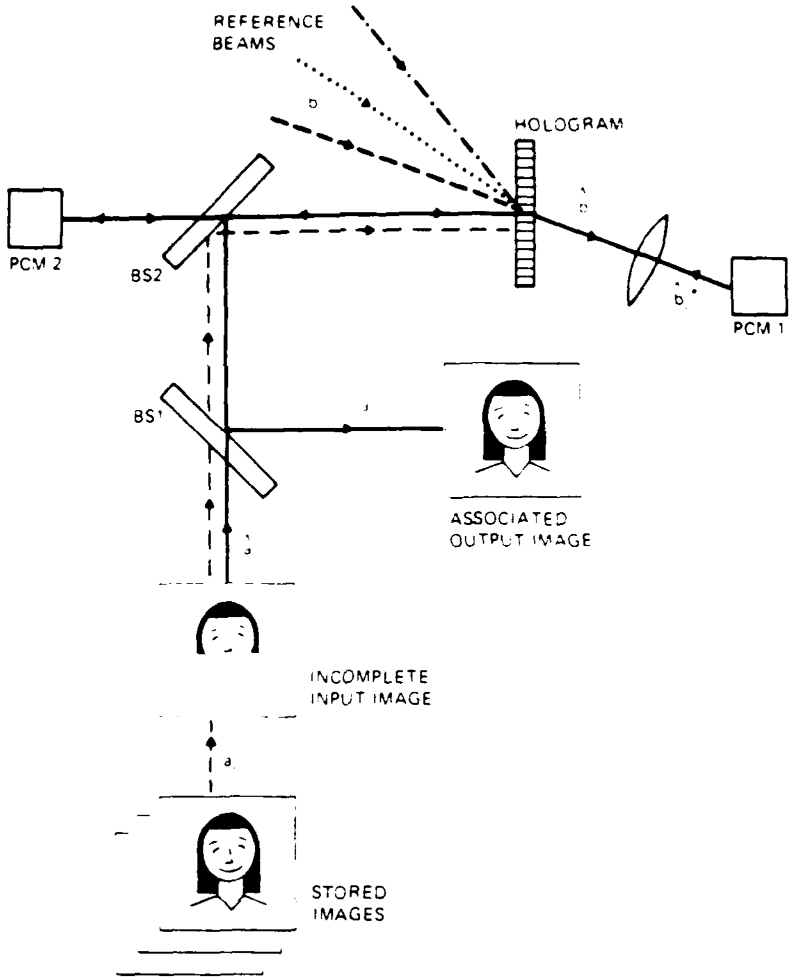

Figure 1. Implementation of all-optical associative memory utilizing holography and phase conjugation.

Related Experimental Results

Preliminary experiments have demonstrated the total reconstruction of a 2-D image when only a partial image addressed the system. This was achieved using the single-pass configuration shown in Figure 2, which consists of a single-image hologram acting as the memory element and a nonthresholding phase conjugate mirror. The hologram was recorded by using a thermoplastic holographic camera. The phase conjugate mirror was produced by degenerate four-wave mixing in the photorefractive crystal $BaTiO_3$. The hologram was generated by recording the interference of an object beam (a transparency is shown in Figure 3(a) and a reference beam at the hologram plane. Upon illumination of the hologram by the object beam, or portion of it, the diffracted beam propagating in the original direction of the reference beam becomes the probe beam for a degenerate four-wave mixing (DFWM) phase conjugate mirror. The signal generated by DFWM is the phase conjugate of the probe, i.e., the reference beam propagating in reverse. When the DFWM signal addresses the hologram, a portion of it is diffracted, recreating the object beam. This object beam has all of the information originally contained in the input image. Thus, by using the input of a partial object image [Figure 3(b)], a portion of the portrait, the complete object image of the entire face is regenerated [Figure 3(c)]. In order to address the issue of angular multiplexing of objects, it has been demonstrated that the device can operate when two images are superimposed on a single hologram (see Figure 4). The two words, *OPTICS* and *WAVES*, were recorded by double exposing the hologram. Each was recorded with its own reference wave. When a portion of either word was input to the system (for example, the *W*), the entire word *WAVES* would appear at the output, suppressing the word *OPTIC*. Conversely, when just a single letter of the word *OPTIC* was input, the complete word was produced at the output. The corresponding experimental results are shown in Figure 5

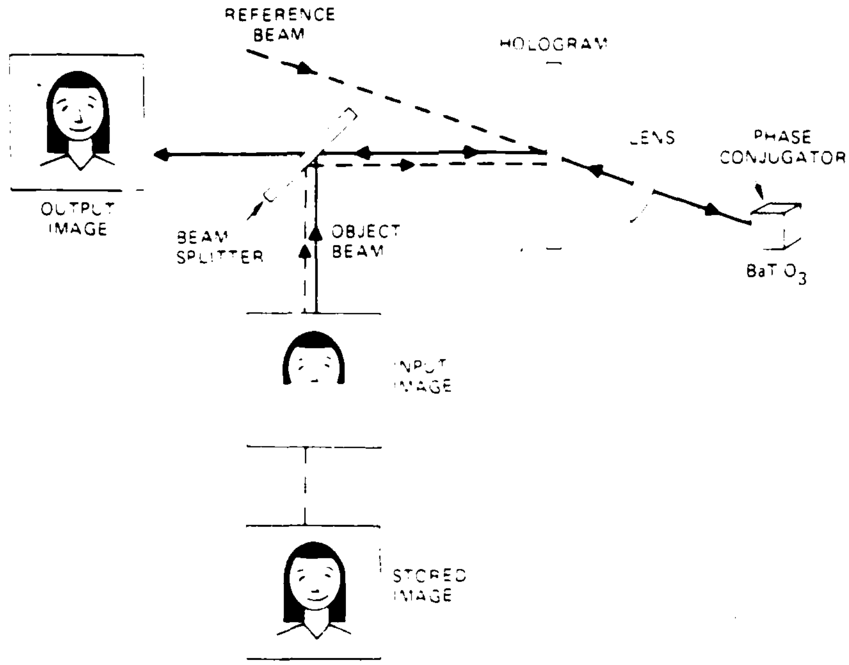

Figure 2. Schematic of 2-D image gray scale experiment.

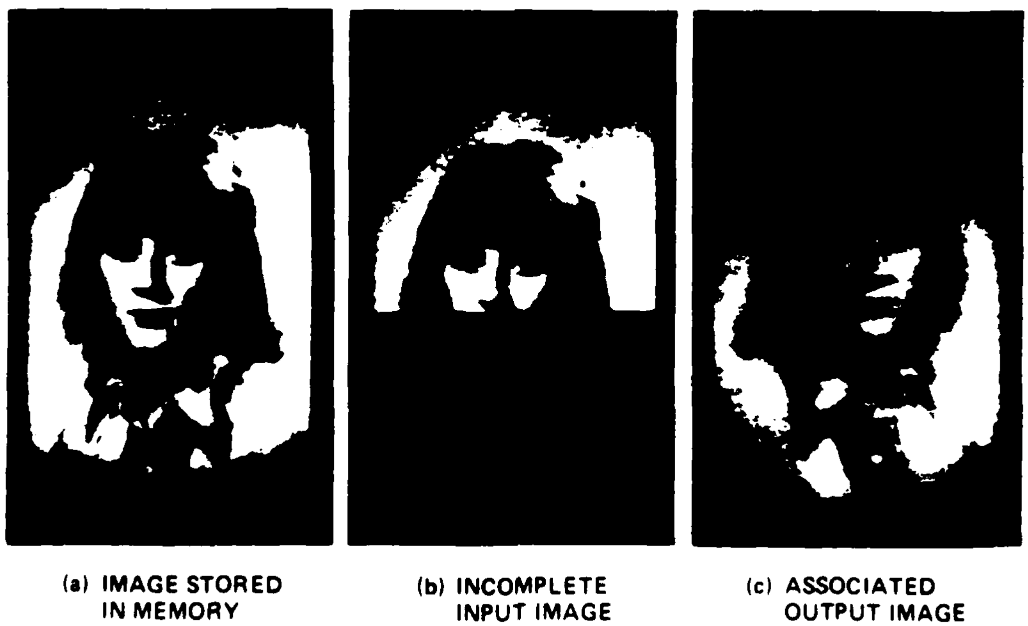

Figure 3. Experimental results of 2-D gray-scale experiment. (a) Image stored in memory. (b) Incomplete input image. (c) Associated output image.

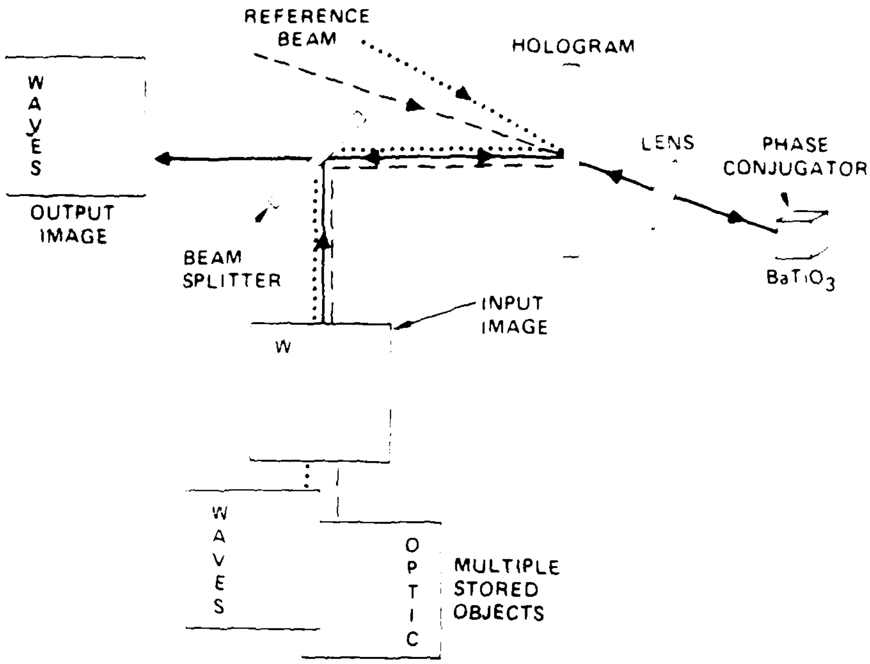

Figure 4. Schematic of multiple-image experiment.

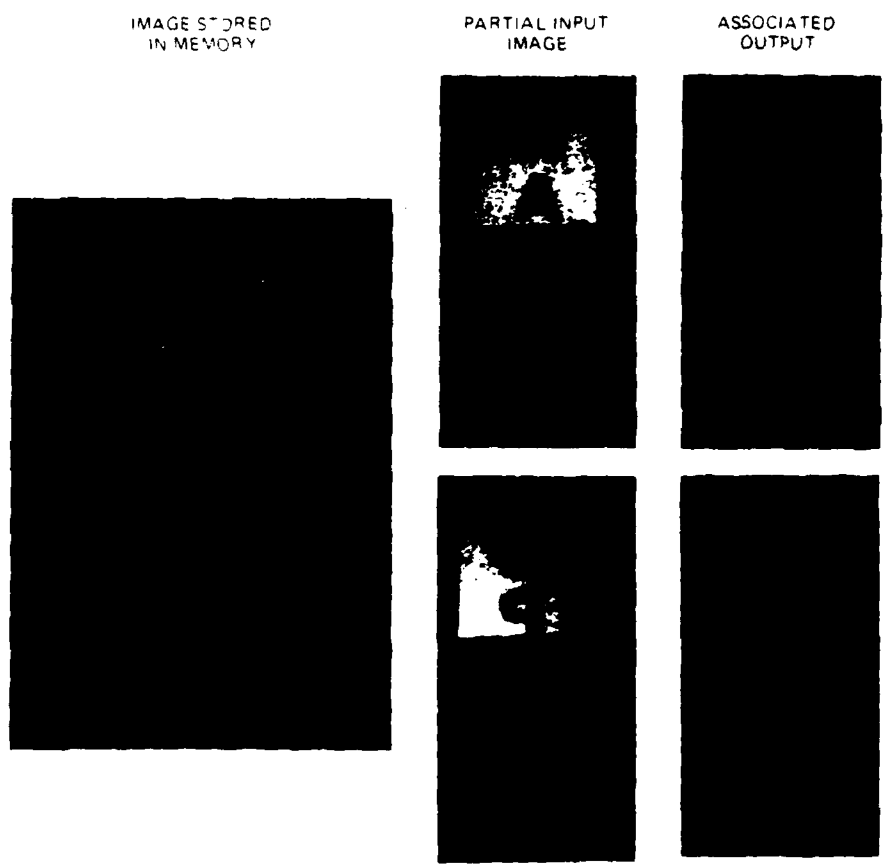

Figure 5. Experimental results of multiple-experiment. (a) Multiple images stored in memory. (b) Partial input image. (c) Associated output image.

Initial experiments demonstrated two key features of an all-optical associative memory and processor. First, a complete 2-D gray-scale image with high spatial frequencies was reconstructed from a partial input. In addition, system selectivity was demonstrated for multiple stored objects by storing a pair of 2-D images and reconstructing either complete image from its associated partial input.

In current experiments, we are investigating an associative memory capable of storing multiple gray-level images in the complete resonator configuration with thresholding. In addition, we are incorporating real-time photorefractive materials, e.g., $LiNbO_3$, as the main holographic memory element.

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4. D. Psaltis and N. Farhat, in *ICO-13 Conference Digest* (International Commission for Optics, Amsterdam, 1984), paper A1-9.

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8. R.J. Collier and K.S. Pennington, Appl. Phys. Lett. **8**, 44 (1966).

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A more extensive analysis that that given in the SPIE paper reproduced above, leads to the following conclusions regarding shift invariance and signal to noise. For one dimensional objects (to compare with Hopfield vectors) we find the signal to noise is:

$$\text{S/Noise} = f \sqrt{\frac{3}{2}} \sqrt{\frac{N}{M-1}} \quad \text{(without nonlinearity)}$$

where N is the number of object resolution cells N=w/d (a given quantity); maximum allowed shift = $\Delta X = W/2$ (minimum $\Delta X = W$); ΔX is the separation between references; output window width = ΔX; M (number of objects)= FOV/ΔX; and f is the fraction of the input correlated with the stored vector.

For two dimensional objects:

$$\text{S/Noise} = \frac{3}{2} f \frac{N}{M-1}$$

The result for the 1-D S/Noise is approximately equal to that derived in our SPIE paper for the Hopfield model. In the Hopfield model the "zero order noise" due to the object autocorrelations is avoided by setting the diagonal terms equal to zero $T_{ii}=o$ (as noted in our SPIE paper). In our case we avoid it by using off-axis references. We should have superior performance compared to Hopfield for the following reasons:

- 2 dimensional images with gray scale are allowed and easily implemented
- much larger N is possible
- fully optical system
- can trade off between amount of shift invariance, number of objects, and object width
- can have good performance in many cases in single pass configuration without thresholding due to the correlation properties of random phase diffusers.

We have made an analysis of the fundamental storage capacity of the Holographic Associative Memory using Ewald Sphere constructions. This analysis concentrated upon the limits due to the wave nature of light and the finite dimensions of the hologram and neglected the material effects of saturation, reciprocity failure, grain noise. Some of these effects, such as the MTF of hologram medium, were included however. A typical result for a thin hologram, assuming an object with 50 cycles/mm maximum frequency, $\lambda=0.5$ μm and a reference beam angle excursion of 23°, is that 10 holograms can be stored. For a thick hologram (100 μm), assuming the same parameters as above, approximately 100 objects could be stored. There is a trade-off in the thin hologram case between the number of objects stored and the degree of translational invariance that can be enjoyed.

Lastly work was begun to implement psuedo conjugation using liquid crystal light valves to replace the phase conjugation of $BaTiO_3$ four-wave mixing as presently employed. The use of psuedo conjugation is possible in this application because our reference waves are plane waves or waves simply derivable from a point source. The possible advantage of using such a scheme ·ould be speed of operation and elimination of the critical alignment of many laser pump beams, as well as the reduction in the power requirements of the laser source.

B. INTENSITY TO POSITION MAPPING SPATIAL LIGHT MODULATORS

The variable grating mode liquid crystal phenomena and device, conceived and developed in this AFOSR program, in its present state of development has too slow a response time (typically tens of milliseconds rise time and hundreds of milliseconds decay time) to be of practical interest for many applications. We have been examining alternative means to provide the very attractive processing function of mapping spatially variant object intensity patterns to position in an extended Fourier space containing object intensity as an additional parameter. Earlier in this program we had conceived and implemented a device based on the refraction of light by an array of liquid crystal prisms whose index of refraction would be locally modulated by the local intensity of object light falling on an underlying photoconductive layer. This device also proved to be too slow and the deflections too nonuniform for practical application because of the need to employ thick liquid crystal prisms with very nonuniform field distributions.

In this period we have begun to examine a variation of this scheme. Instead of an actual array of physical prisms, a set of interdigitated electrodes on a thin uniform liquid crystal layer, again sitting atop a photoconductor layer, form a set of virtual prisms by voltage induced index gradients whose strength depends upon the local object light intensity falling upon the photoconductor. The deflection that can be achieved, in either device, depends only upon the maximum phase excursion in the liquid crystal. The gradient index device is expected to perform better because of more uniform field distributions across each pixel. This work is in progress.

SECTION 3

PERSONNEL ASSOCIATED WITH THIS PROGRAM

The professional personnel associated with this research at HRL during this period were B.H. Soffer, principal investigator and program manager, E. Marom, Y. Owechko, and G.J. Dunning. C.C. DeAnda provided technical assistance.

SECTION 4

PUBLICATIONS PRESENTATIONS AND PATENTS RESULTING FROM AFOSR SUPPORT OF THIS PROGRAM

A. PUBLICATIONS AND PRESENTATIONS

1. "Approaches to Nonlinear Optical Processing in Real Time," presented at the International Commission for Optics Eleventh Meeting, Madrid, 1978.

2. "Real-Time Nonlinear Optical Processing with Liquid Crystal Devices," presented at the International Computing Conference, London, 1978.

3. "Real-Time Nonlinear Processing with Halftone Screens," presented at the OSA Annual Meeting, San Francisco, 1978.

4. "New Method for Real-Time Nonlinear Optical Processing," presented at the OSA Annual Meeting, San Francisco, 1978.

5. Invited paper presented at the Gordon Conference, Ventura, CA, June 1980.

6. "Optical Computing with Variable-Grating Mode Liquid Crystal Light Valves," 1980 Int. Opt. Computing Conference IOCC, April 1980, Washington, DC.

7. "Variable Grating Mode Liquid Crystal Device for Optical Processing and Computing," Eighth Int. Liquid Crystal Conf., Kyoto, July 1980.

8. Variable Grating Model Liquid Crystal Device for Optical Processing," SPIE Tech. Symposium, Los Angeles, February 1980.

9. "Parallel Optical Analog-to-Digital Conversion Using the LCLV," High Speed A/D Workshop, Portland, OR, February 1980.

10. "Real-Time Parallel Optical Analog-to-Digital Conversion, Optics Letters, 5, 129 (1980).

11. "Optical Logic with Variable-Grating Mode Liquid Crystal Devices," Optics Letters 5, 398 (1980).

12. "Variable Grating Mode Liquid Crystal Device for Optical Processing and Computing," Molecular Crystals and Liquid Crystals 70, 145-161 (1981).

13. "Silicon Liquid Crystal Light Valves for Optical-Data Processing," Integrated Optics and Millimeter and Microwave Integrated Circuits, SPIE 317, November 1981.

14. "Intensity-to-Spatial Frequency Transformations in Optical Signal Processing," Transformations in Optical Signal Processing, SPIE 373 (1981).

15. "Theoretical and Experimental Polarization Properties of the Variable Grating Liquid Crystal Structure," presented at Annual Meeting of Optical Society of America, Orlando, FL, October 1981.

16. "Technical Applications of the Variable Grating Mode Effect," presented at 4th Liquid Crystal Conference, Tbilishi, Georgia, USSR, September 1981.

17. "Real-Time Parallel Logarithmic Filtering," Optics Letters, 7, 451-453 (1982).

18. "Physical Characterization of the Variable Grating Mode Liquid Crystal Device," presented at SPIE Los Angeles Technical Symposium - Advances in Optical Information Processing, SPIE, 388, January 1983. Also Opt. Eng., 22, 687-694 (1983).

19. "Sequential Optical Logic Implementation," presented at Annual Meeting of Optical Society of America, Tucson, AZ, October 1982. Applied Optics, 23, 3455 (1984)

20. "The Application of Silicon Liquid Crystal Light Valves to Optical Data Processing," presented at the SPIE Los Angeles Technical Symposium - Advances in Optical Information Processing - SPIE, 388, January 1983.

21. "The Application of Silicon Liquid Crystal Light Valves to Optical Data Processing: A Review" presented at Optical Information Processing Conference II, NASA, Langley, VA, August 1983.

22. "Liquid Crystal Optical Processing," invited keynote paper presented at 13th European Solid State Device Research Conference, University of Kent, Canterbury, England, September 1983. Inst. Phys. Conf. Ser. 69, p. 121-139 (1984)

23. "Polarization Properties of the Variable Grating Mode Liquid Crystal Device", Optics Letters 9, 171 (1984) (with A. Tanguay et al.).

13. "Silicon Liquid Crystal Light Valves for Optical-Data Processing," Integrated Optics and Millimeter and Microwave Integrated Circuits, SPIE 317, November 1981.

14. "Intensity-to-Spatial Frequency Transformations in Optical Signal Processing," Transformations in Optical Signal Processing, SPIE 373 (1981).

15. "Theoretical and Experimental Polarization Properties of the Variable Grating Liquid Crystal Structure," presented at Annual Meeting of Optical Society of America, Orlando, FL, October 1981.

16. "Technical Applications of the Variable Grating Mode Effect," presented at 4th Liquid Crystal Conference, Tbilishi, Georgia, USSR, September 1981.

17. "Real-Time Parallel Logarithmic Filtering," Optics Letters, 7, 451-453 (1982).

18. "Physical Characterization of the Variable Grating Mode Liquid Crystal Device," presented at SPIE Los Angeles Technical Symposium - Advances in Optical Information Processing, SPIE, 388, January 1983. Also Opt. Eng., 22, 687-694 (1983).

19. "Sequential Optical Logic Implementation," presented at Annual Meeting of Optical Society of America, Tucson, AZ, October 1982. Applied Optics, 23, 3455 (1984)

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28. "Optical Holographic Associative Memory using a Phase Conjugate Resonator". Proceedings SPIE Symposium on Optical Computing, Vol. 625 pp 205-213, Los Angeles, January 1986.

29. "Associative Holographic Memory with Feedback Using Phase Conjugate Mirrors". Invited paper presented at the Optical Society of America Topical Meeting on Holography, Honolulu, April 1986.

30. "Associative Memory in a Phase Conjugate Resonator Cavity Utilizing a Hologram" Proceedings of the Nueral Networks for Computing Conference, Snowbird UT, April 1986.

31. "All Optical Associative Memory Incorportaing Holography and Phase Conjugation" Presented at CLEO, San Francisco, June 1986.

32. "Holographic Associative Memory Employing Phase Conjugation" Proceedings SPIE Vol. 684, San Diego, August 1986 also presented at the International Optical Computing Conference, Jerusalem Israel July 1986.

B. PATENTS GRANTED

1. "Methods and Apparatus for Optical Computing and Logic Processing by Mapping of Input Optical Intensities Into Position of an Optical Image," United States Patent 4,351,589, September 28, 1982.

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